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MSAT-X ELECTRONICALLY STEERED PHASED ARRAY ANTENNA SYSTEM

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ABSTRACT

A low profile electronically steered phased array has been successfully developed for the Mobile Satellite Experiment Program (MSAT-X), under the contract with Jet Propulsion Laboratory (JPL). The newly invented cavity-backed printed crossed-slot was used as the radiating element. The choice of this element was based on its low elevation angle gain coverage and low profile. A nineteen-way radial type unequal power divider and eighteen three-bit diode phase shifters constitute the beamformer module which is used to scan the beams electronically. A complete hybrid mode pointing system, which uses an external rate sensor and internal error signals to optimize the angle tracking accuracy, has also been developed. The major features of the developed antenna system are broad space coverage, low profile (0.75 inch exclusive of the input RF connector and beam control DC connector), and its fast acquisition and tracking performace, even under fading conditions. Excellent intersatellite isolation (better than 26 dB) was realized which will provide good quality mobile satellite communication in the future.

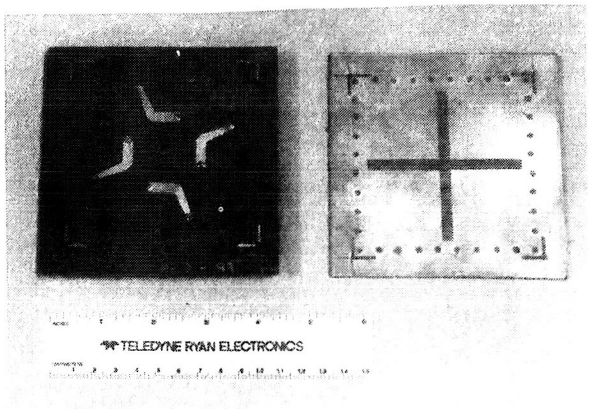
INTRODUCTION

The development of low cost vehicle phased array for the MSAT-X program has been a challenging task for the antenna designer. Broad spectrum of considerations have been taken into account in the design phase so that the best antenna system was successfully developed during the contrat with JPL. The design philosophy of the antenna array, beamformer and pointing system as well as the measured array performance will be discussed in the following sections.

ANTENNA ARRAY DESIGN

Among the low profile antenna candidates, the crossed-slot and patch element were considered. The cavity-backed printed stripline fed crossed-slot was selected, however, because it has (1) wider beamwidth, (2) better gain and axial ratio at low elevation angle, and (3) thinner for the same operating frequency band than that of patch antenna.

The stripline fed crossed-slot element is basically made of two separate boards. As shown in Figure 1, crossed-slot was etched on a single sided copper clad substrate and the stripline feeders was etched on another board of the same thickness. The two boards were bonded together. A set of plated through holes were required to form a cavity wall. Circular polarization was obtained by feeding the crossed-slot in phase quadrature via a integrated feed network of a 90 degrees branch line hybrid and two 180 degrees corporate circuit (Figure 2). The four point feed with symmetrical arrangement and phase rotations (0-90-180-270 degrees) is required to eliminate the higher order mode inside the cavity so that the crossed-slot can radiate efficiently.



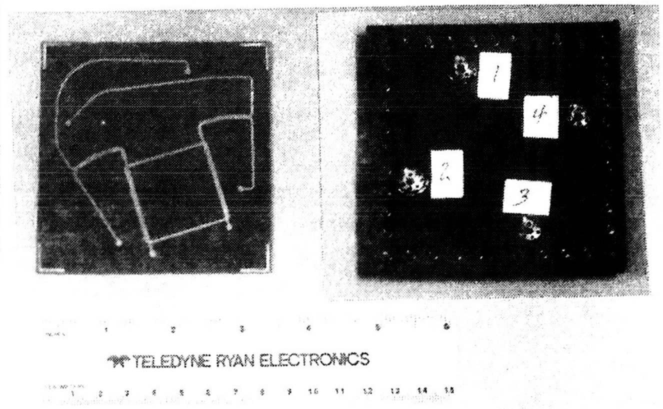


Fig. 1. Photo of the crossed-slot

Fig. 2. Photo of the hybrid feed network

The array aperture design was performed so that the required performance be achieved at the lowest cost. The major constraints on the aperture design are: (1) intersatellite isolation (20 dB), (2) array gain (10 dBic), (3) array thickness (within 1 inch), (4) manufacturing cost ($1500.00), (5) multipath rejection capability and (6)backlobe level (12 dB).

The design philosophy is using minimum number of elements and maximum usage of the aperture as well as avoiding the grating lobes. After the detail trade off analysis, a nineteen crossed-slot element array with triangular lattice arrangement was chosen. The element spacing was 3.9 inch. Proper amplitude taper of three circular rings of relative power -6dB, -5.2 dB, and -3 dB (starting from the outside going towards the center) was used to reduce the sidelobe level so that the required 20 dB intersatllite isolation can be maintained. Array size was 22 inches which includes the mounting space. Three-bit diode phase shifter was selected to steer the antenna beam.

BEAMFORMER DESIGN

The beamformer network which consists of two major components, an unequal nineteen way power divider and a three bit phase shifter, had been successfully developed on a 20.6" diameter microstrip plane, as shown in Figure 3. The beamformer network will continue to present design challenge in the future for the low cost production with high performance and reliability.

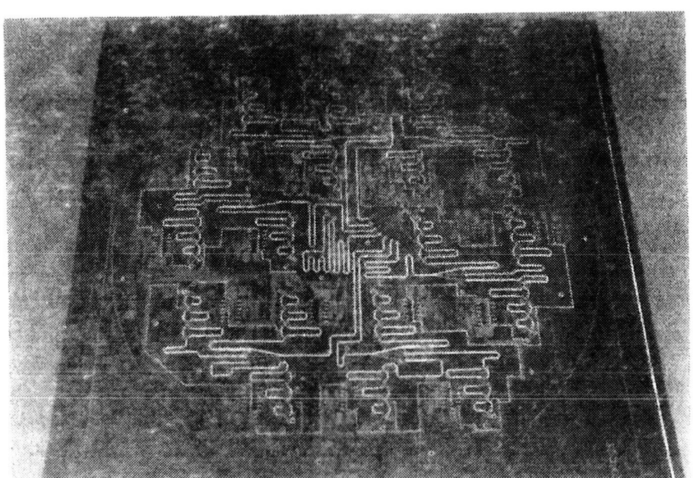


Fig. 3. Beamformer boards of the array

The unequal power divider consists of an equal seven way power divider followed by six unequal three way dividers. The divider design is based on the Wilkinson divider concept which splits the 50 ohm line into two or more quarter wave sections of the right impedance to preserve a 50 ohm impedance match. Balancing resistors bridge each arm at the ends of the matching sections. These resistors keep the match when outputs are not balanced. For unequal divisions additional quarter wave sections are required. Computer optimization using the "Touchstone" program was used to design the impedance and resistor values.

The three bit phase shifters were based on the switched line principle. This was selected to give the least phase shift error over the operating band from 1545 MHz to 1660 MHz, compared to that of the hybrid coupled phased shifter. The switched line phase shifter projects an 11 degrees error while the hybrid phase shifter projects a 19 degrees error over the same frequency band. The disadvantage of the switched line design is that twice as many diodes are required. However, the switched line configuration can be redesigned with the back to front pin diodes at common points. This leads to the possibility of using monolithic diode pairs so that the cost of antenna system will be further reduced.

POINTING SYSTEM DESIGN

A complete hybrid mode pointing system, which uses an external rate sensor and internal error signals to optimize the angle tracking accuracy over a wide of contingencies, has also been developed. Basically, the fast response operations are controlled by the angle rate sensor while the radio link corrects the rate sensor errors. Because the rate sensor bias error changes slowly, the radio link data is averaged over a 30 seconds period before correcting the rate sensor. This will filter out any attitude perturbations, shadowing or fading (multipath) effects in the radio link.

When the rate sensor is disconnected, the rate sensor correction is eliminated and the radio link loop is automatically increased. This allows somewhat less accurate but still adequate satellite tracking on pilot signal alone;however, it will no longer be able to follow vehicle turns during signal outages.

The sequential lobing dither of the radio link is held to plus and minus 1.5 degrees under normal signal strength conditions in order to have maximum intrersatellite isolation. The dither magnitude is only increased if signal level drops. This is done automatically by sensing the strength of the pilot signal. The dither frequency is a modifiable parameter which can be adjusted between 10 and 200 Hz.

The elevation angle of the antenna beam is controlled by searching for maximum signal strength. Because of the wide antenna beamwidth and the generally slow variation of satellite elevation angle, this search is done at rate of one incremental beam per second from 30 degrees through 70 degrees (from the array broadside) in increments of 5 degrees. The total number of incremental elevation beam is nine. The low search rate also separates the elevation servo information from the azimuth servo to prevent cross-coupling.

ARRAY ASSEMBLY

A total of five layers of substrate material board were used to construct the whole array which consists of antenna array module and the beamformer module as shown in Figure 4. The antenna array module consists of four boards - a top crossed-slot board, a stripline excitation feeder board, a hybrid/corporate feed network board and a bottom ground board. The top two boards (same thickness) of the crossed-slot array elements were etched on a single sided, copper clad teflon fiberglass board. The thickness of the board were 0.09 inch and 0.125 inch for the breadboard unit #1 and #2 array, respectively. The thicker board used for the unit #2 is to increase the antenna bandwidth. A set of plated through holes around the crossed-slots were required to form the cavity wall for the crossed-slot element. The bottom two boards with thickness of 0.031 inch each constitute

the integrated stripline hybrid/corporate feed network. The beamformer board and the 0.125 inch stiffner plate were bonded together using silver-bonded epoxy to form the beamformer module.

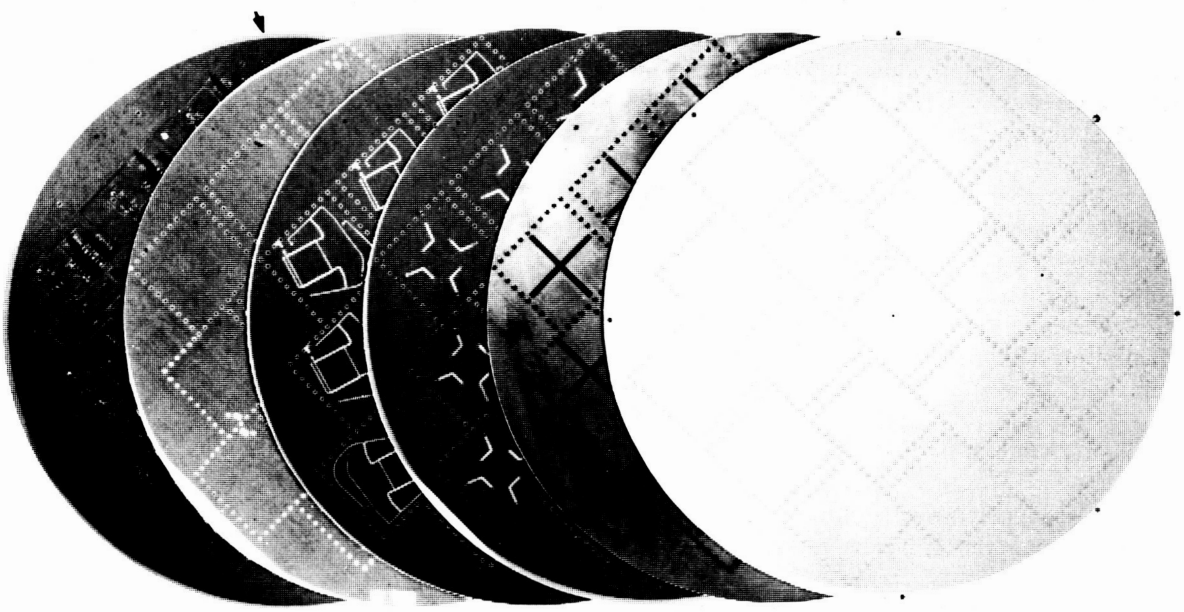


Fig. 4. A photo to show the five layers of MSAT-X array design

The antenna array module were key together with the beamformer module and then were bolted together with the back cover leaving an air gap of 0.2 inch between the beamformer circuit and the cover. Figure 5 shows a final assembled MSAT-X array. A very thin (0.002 inch) painted polyurethane type radome was employed to provide protection against the enviroment.

Fig. 5. Final assembled MSAT-X phased array

The total thickness of the array unit #1 and #2 were 0.68 inch and 0.75 inch, respectively. The thickness of the final production array will be reduced to 0.625 inch when the 0.125 inch stiffner plate in between the beamformer board and the antenna array board are removed.

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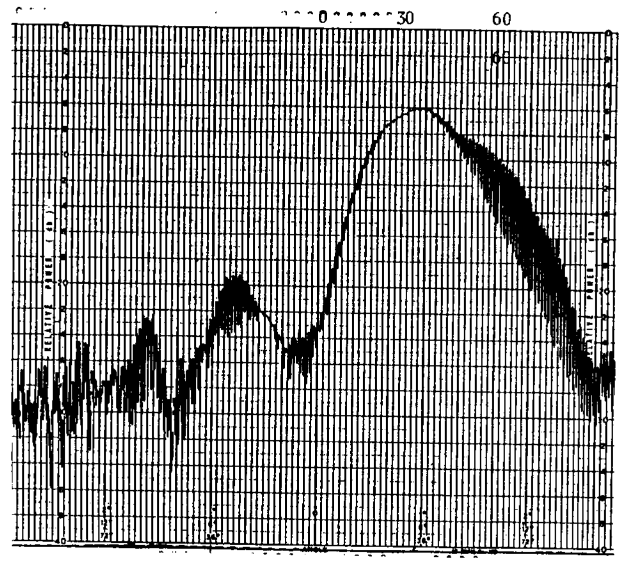
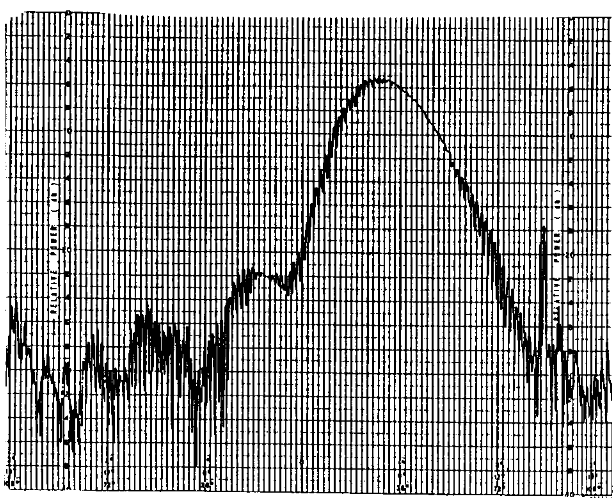
MEASURED ARRAY PERFORMANCE

Extensive measurements were performed during the contract with JPL. Typical measured array patterns are shown in Figures 6 and 7. Well behaved array patterns were observed in all the measured data. Excellent axial ratio (<5 dB) of the array pattern was achieved within 95% of the required space coverage across the operating frequency band.

The measured array performance is summarized in Table 1. These results show that all the requirements were satisfied except the gain. However, it is believed that the 10 dBic gain at 20 degrees elevation angle will be realized in the future through the optimization of the crossed-slot excitation feeder design and the beamformer aperture distribution. Detail will be discussed in the meeting.

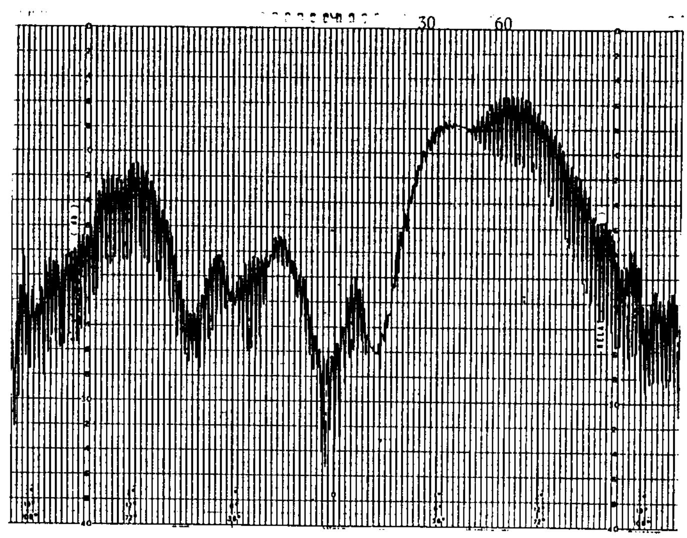


(a) 1545 MHz

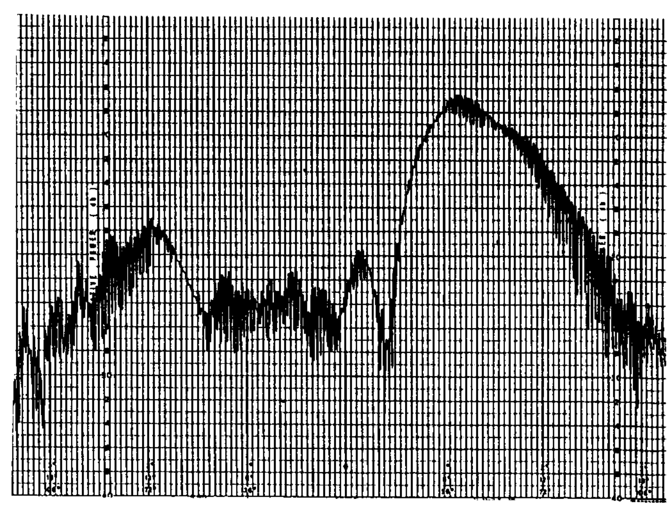


(b) 1660 MHz

Fig. 6 Measured elevation array patterns at scan angle of 40 degrees away from array normal



(a) 1545 MHz



(b) 1660 MHz

Fig. 7 Measured elevation array patterns at scan angle of 60 degrees away from array normal

Table 1. Summary of Measured Array Performance			
	Measured Value		
	Unit #1	Unit #2	Spec
Gain at 20° elevation angle (dBic) 1545 MHz	9.2 (average)	9.3 (average)	10
1660 MHz	7.7 (average)	8.3 (average)	10
Intersatellite Isolation (dB)	26	26	20
Backlobe (dB)	12 (95%) <12 (5%)	12 (95%) <12 (5%)	12
Multipath Rejection (dB) (pattern dropoff from 20° to 0° elevation	>6	>6	6
Antenna Thickness (inch) (Exclusive of RF Connector)	0.68	0.75	<1

CONCLUSIONS

An L-band car-top comformal phased array has been sucessfully developed for the mobile satellite communications. The following conclusions can be drawn from the development work with JPL:

(1) The printed cavity-backed stripline fed crossed-slot element is proven to be the best radiating element for the MSAT phased array.

(2) The measured array gain at 70 degrees from the array broadside is 9.3 dBic and 8.3 dBic for the frequency 1545 MHz and 1660 MHz, respectively. 10 dBic gain across the frequency band is achievable in the future.

(3) Excellent intersatellite isolation (26 dB) was achieved which is better than the requirement (20 dB).

(4) The total thickness of the developed array is 0.68 inch and 0.75 inch for the unit #1 and #2, respectively.

(5) The multipath rejection requirement was satisfied.

(6) The backlobe level is better than 12 dB in 95% of the required space coverage. The worst backlobe is 6 dB when the array was scanned to 70 degrees from the array broadside at certain azimuth angles.